DARRIEUS ROTOR AERODYNAMICS*

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INTRODUCTION

Darrieus wind turbines are relatively simple devices. Fixed geometry blades, usually only two or three in number, rotate about a vertical axis providing power to ground mounted power conversion or absorption machinery. No yaw control or power regulation systems are required. This simplicity, however, does not extend to the rotor's aerodynamics. The blade elements travel along circular paths through air whose relative speed and direction are constantly changing. The blade elements operate both unstalled and stalled with aerodynamic stall providing the rotor's inherent power regulation. The blade elements encounter their own wakes and those generated by other elements. These features combine to cause the thorough analysis of Darrieus rotor aerodynamics to be a challenging undertaking.

While it is impossible to fully document the accomplishments in the area in a paper of this length, a reasonable summary can be made. The following is intended to be such a summary.

PERTINENT AERODYNAMIC PHENOMENA

The unsteady, nonlinear aerodynamics with interference can be modeled. Particular components are as follows:

A. Interference

The blade/blade wake interaction presents the most fundamental modeling problem. The simplest approach was taken by Templin (1) with his single streamtube theory. Templin established a streamtube bounded by the rotor and equated the loss of the air's windwise momentum to the circumferentially averaged windwise gain in momentum of the blades. Calculations are performed for a single blade whose chord equals the sum of the chords of the actual rotor's blades. Airfoil characteristics were introduced through the application of blade element theory. Upwind and downwind passages of the blades through the tube were considered in an average sense as well. This approach gives predictions of rotor performance (average torque per revolution) only.

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Numerous investigators (References 2 and 3, for example) extended Templin's approach by considering the single streamtube to be comprised of a number of adjacent and aerodynamically independent smaller streamtubes. Again, the conservation of windwise momentum was applied and blade element theory used, but here to each component streamtube. This allowed element airfoil characteristics based on local Reynolds number (rather than an average) to be used and the effects of wind shear to be considered. Upwind and downwind passages were averaged for each streamtube using a single blade whose chord was equal to the sum of the rotor's blade chords. These multiple streamtube approaches do provide some estimate of blade torque vs. circumferential position, but these predictions are generally poor. The up- and downwind averaging forces an unrealistic symmetry to the loads generated in the upwind and downwind portions of the flowfield, and the streamtubes are taken to be aerodynamically independent. Estimates of rotor performance (average torque per revolution), however, are generally good as long as the rotor loading is relatively light (low to moderate solidities and tipspeed ratios).

Further improvements in the multiple streamtube models have been reported recently (4, 5, 6). The basic difference between these newer codes and those discussed above is that the upwind and downwind passages through each streamtube are considered separately. This addition removes the false symmetry imposed by the earlier models and effectively allows the consideration of nonsymmetrical blade elements. Blade torque vs. circumferential position predictions via the double pass multiple streamtubes are difficult to validate due to the lack of single blade torque data. Examination of two bladed (summed) torque histories show that this approach appears reasonable.

A second class of interference models are those based upon vortex representations of the blades and their wakes. These vary in complexity from relatively simple fixed wake analyses in two dimensions considering unstalled blades only (7, 8) to a free wake model (9) in a fully unsteady environment considering both stalled and unstalled elements in three dimensions. The Reference 9 model represents each blade by a lifting line whose strength changes as a function of both circumferential position and spanwise location. The model treats nonsymmetrical airfoils and predicts circumferential load variations quite accurately, but at the cost of computer run times (up to 5000 seconds on CDC 7600) which are orders of magnitude greater than those required by even the most complex momentum-based models. Figure 1 shows a comparison between one such prediction and measurements (10) from a blade accelerometry survey on the Sandia National Laboratories' 17-m diameter research turbine. The comparison is particularly significant as the turbine is operating with highly nonlinear aerodynamics in a flowfield with a significant amount of asymmetry.

Worthy of note is a hybrid momentum/vortex code developed by Wilson and Walker (11). The model was designed to combine the fast computational times of the streamtube codes and the essential interference capabilities of the vortex-based codes. As in the conservation of momentum-based models, the total induced velocity (rotor velocity deficit) is obtained by equating the windwise momentum change of the incident air to the mean blade force in the windwise direction. Fore-and-aft blade interference is treated by considering vorticity shed by the blade elements as they traverse their circular trajectories. These considerations quickly yield the relationship between the upwind and downwind induced velocities (velocity deficits). These are used with the previously obtained total deficits to find the upwind and downwind deficits. The scheme appears to make very good estimates of rotor performance. A typical example is shown in Figure 2.

B. Dynamic Stall

A Darrieus rotor blade element experiences changes in angle-of-attack, α, as it traverses its circular trajectory. For high enough values of ambient windspeed, the element's static stall value, α_s, will be exceeded over portions of the circumferential path. The time rate of change of angle-of-attack, $\dot{\alpha}$, causes delays in both the onset of and the recovery from stall to values of α above and below α_s, respectively. A hysteresis is added to the airfoil characteristics. This is termed dynamic stall and results in increasing both rotor power output and peak aerodynamic torques at a given windspeed. These effects significantly impact drive train/generator sizing and system reliability.

The dynamic stall problem is extremely complex. Factors influencing it are airfoil geometry, Reynolds number, reduced frequency, angle-of-attack (both mean value and amplitude) and Mach number. The phenomena has been successfully treated in the Darrieus rotor application (12, 9, 14) by using an empirical model (13). A comparison between experimentally observed rotor power outputs and those predicted by a double pass multiple streamtube code (14) using this empirical model is given in Figure 3. A comprehensive treatment of dynamic stall in the wind turbine context is given in Reference 15.

C. Apparent Mass

Another unsteady effect is due to fluid inertia and is treated succinctly by Strickland (9). Using an analytical description of the potential flow about a two-dimensional flat plate, it is shown that there are noncirculatory forces proportional to airspeed changes and angular velocity. These fall into the category of apparent mass effects. Strickland states that the normal force contribution is negligibly small, but that the apparent mass tangential component needs to be considered. Further, there is a change in the 1/4 chord pitching moment directly traceable to fluid inertia.

D. Circulatory Effects

The blade element's pitching necessitates an adjustment to the strength of the element's circulation in order to continue satisfying the Kutta condition. Again, using the potential flow about a two-dimensional flat plate, Strickland (9) shows that the effect of pitching circulation on the blade tangential force is equal and opposite that due to fluid inertial effects if the tangential force is determined based upon flow conditions (angle-of-attack) at the blade element's mid-chord. A similar simplification results for the normal force. Pitching circulation is included if the normal force is determined from flow conditions (angle-of-attack) at the element's 3/4 chord point. The normal force, however, is still taken as acting at the 1/4 chord. There is no change in the 1/4 chord pitching moment due to pitching circulation. Figure 4 shows the effects of including the apparent mass and pitching circulation terms on a two-dimensional, symmetrically bladed turbine.

An alternative way of treating pitching circulation is with the concepts of "virtual camber" and "virtual incidence" (16). These concepts are based upon the postulate that a symmetrical airfoil section operating in a curvilinear flowfield is equivalent to a cambered version of that airfoil operating in a rectilinear flowfield. The degree of camber depends upon the ratio of chord to radius of rotation, and the shape of the camber line is a function of the location of the perpendicular intersection of the position vector from the axis of rotation and the blade chord.

BLADE SECTION CONSIDERATIONS

All of the aerodynamic models described above require blade element section data for their use. Certain difficulties have arisen in obtaining these data due to the Darrieus blade airfoil's operation over ranges in both angle-of-attack and Reynolds number not found in typical aeronautical applications. It has been necessary to synthesize airfoil characteristics in order to extend the coverage ($10^4 < Re < 10^7$, $-180° < \alpha < 180°$) of standard airfoil data and to economically assess the desirability of sections designed specifically (natural laminar flow shapes, for example) for the Darrieus application. The approach used at Sandia National Laboratories is to calculate section characteristics in the linear and early stall regimes using the panel method developed by Eppler (17). Late- and post-stall values are taken from a series of wind tunnel tests on NACA-00XX profiles. It is postulated that at these high angles-of-attack with their accompanying separated flows, the characteristics are independent of both section geometry and Reynolds number. The choice of value of α where the transition between calculated and measured properties takes place is somewhat arbitrary. For the NACA-00XX profiles at Sandia National Laboratories, the 17-m diameter research turbine there was used to define the switchover point. Performance predictions made by the conservation of momentum-based aerodynamic model DARTER (3) using various switchover points were compared to NACA-0015 bladed 17-m diameter actual performance (18). The best comparison gave the transition values of α. The same values of α were assumed appropriate for other NACA-00XX sections. A compilation of these data is presented in Reference 19. No similar luxury exists for assessing other candidate airfoils for VAWT applications. It is unfortunate that knowledge of stall region behavior of most sections is so sparse, as it is this flow regime which governs the important stall regulation feature of Darrieus turbines.

Another airfoil consideration beyond those of lack of availability of data over sufficiently wide ranges in α and Re is the question of using section data obtained in rectilinear flow situations in flowfields which are curvilinear. The surface pressure distributions about pitching airfoils operating over curvilinear paths differ from those found on nonpitching, nonrotating sections. These differences would alter the boundary layer structure and therefore the section characteristics. These changes would not be reflected in the potential flow analyses noted earlier. Certainly the dynamic stall phenomena is a direct result of the interaction between the pitching element's pressure distribution and boundary layer.

CONCLUDING REMARKS

Darrieus turbines operate with unsteady, nonlinear, interfering aerodynamics. A great deal of progress has been made in describing these aerodynamics since the Darrieus concept was rediscovered by Templin, South, and Rangi in the early 1970's. A large number of performance/loads models considering various relevant aerodynamic phenomena exist but there are very few experimental data available by which these models' loads vs. blade circumferential position predictions may be validated. Also, far more has been published regarding turbines using symmetrically sectioned blade elements than for those with asymmetrical profiles. These cambered and/or preset pitched elements will likely be used in the future as they promise lower peak loads and increased reliability. It would appear that future work needs to be concentrated on validating an inexpensive (to use) loads model which can satisfactorily treat nonsymmetrical blade sections and on blade section behavior in the dynamic, curvilinear environment.

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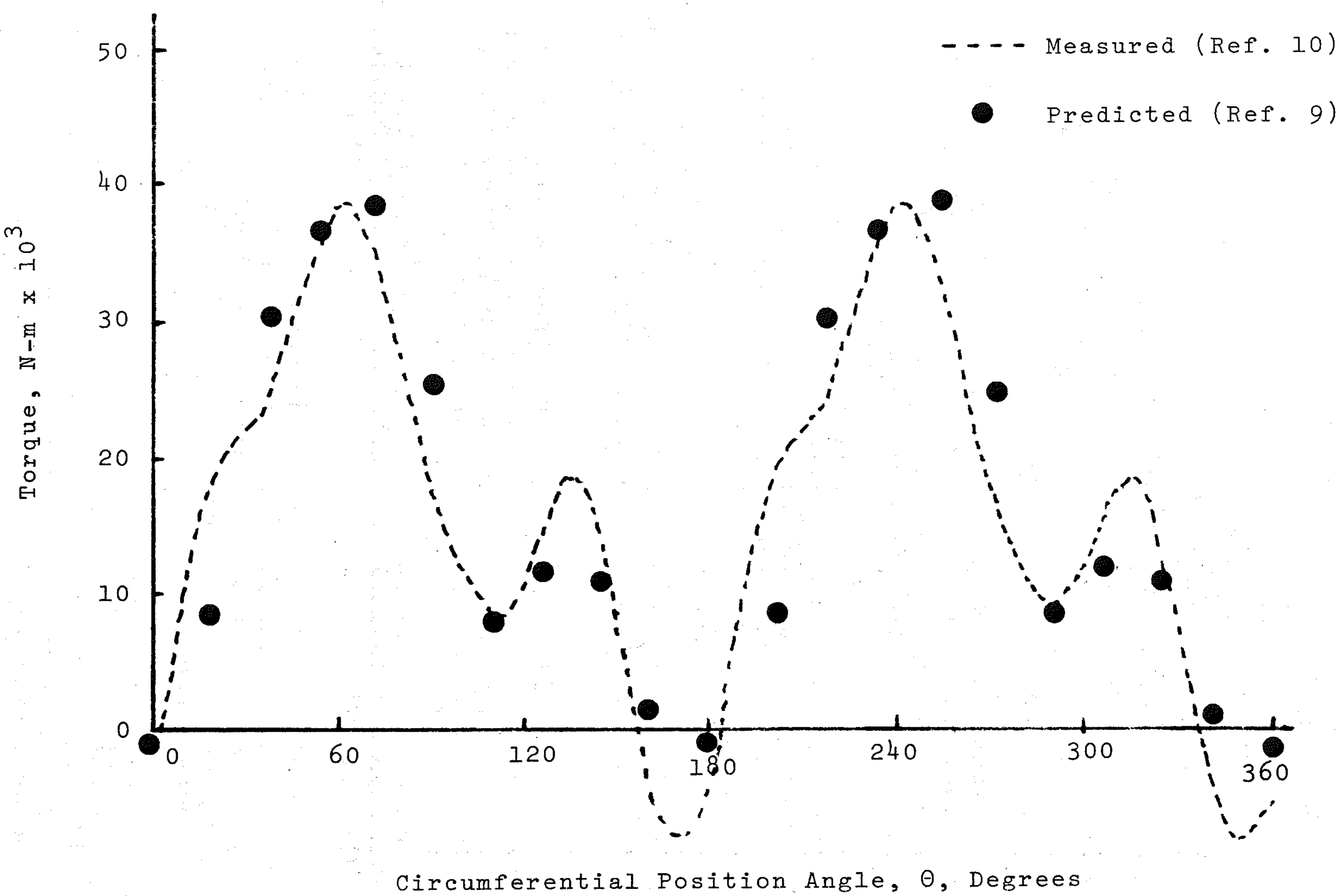

Figure 1. Rotor Aerodynamic Torque, SNL 17-m-Diameter Research Turbine, 2 Blades, NACA 0015 Section, 61 cm Chord, ω = 50.6 rpm, X = 2.18

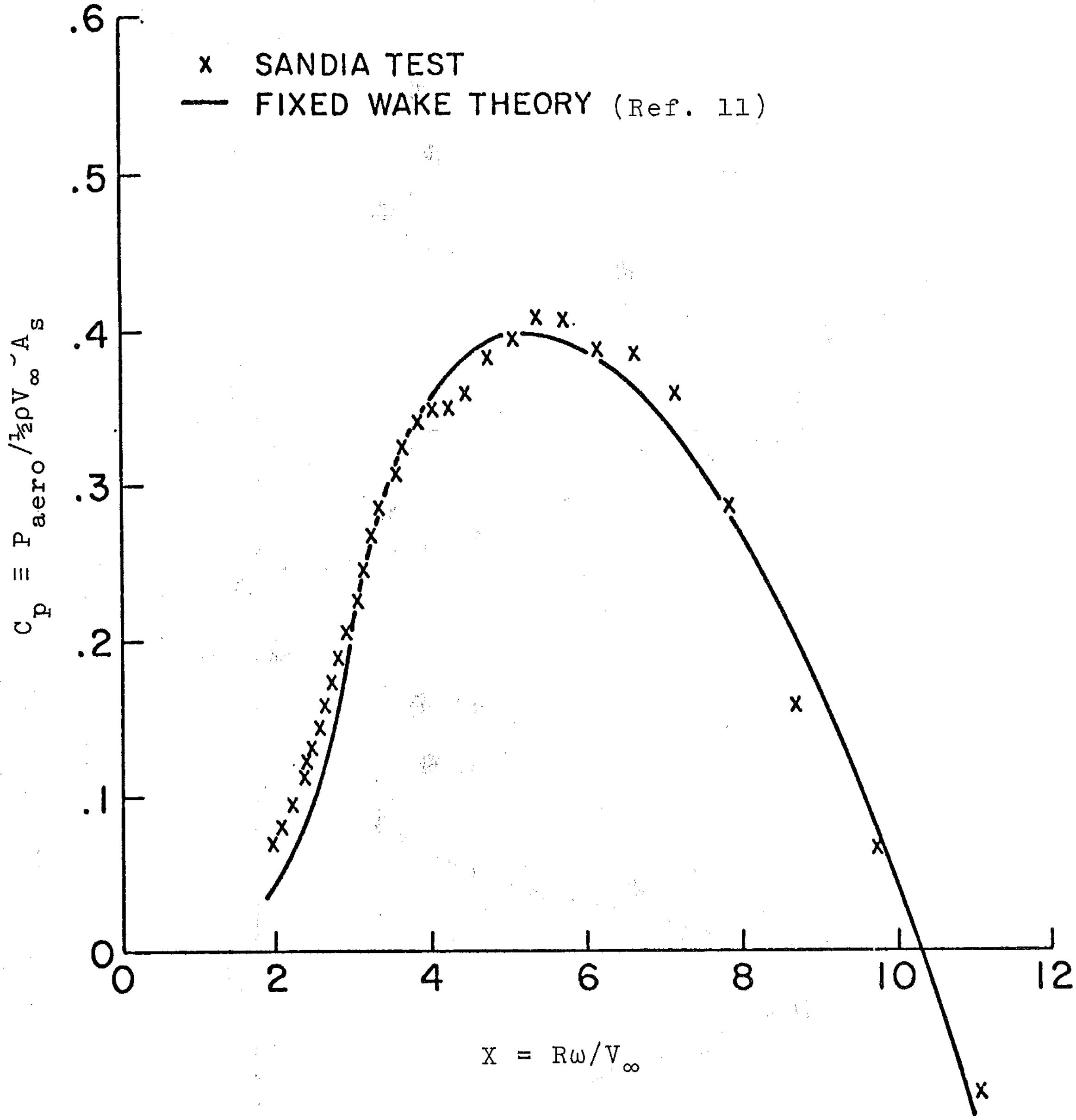

Figure 2. Fixed Wake Theory and Test Results, SNL 17-m-Diameter Research Turbine, 2 Blades, NACA 0015 Section, 61 cm Chord, ω = 42.2 rpm

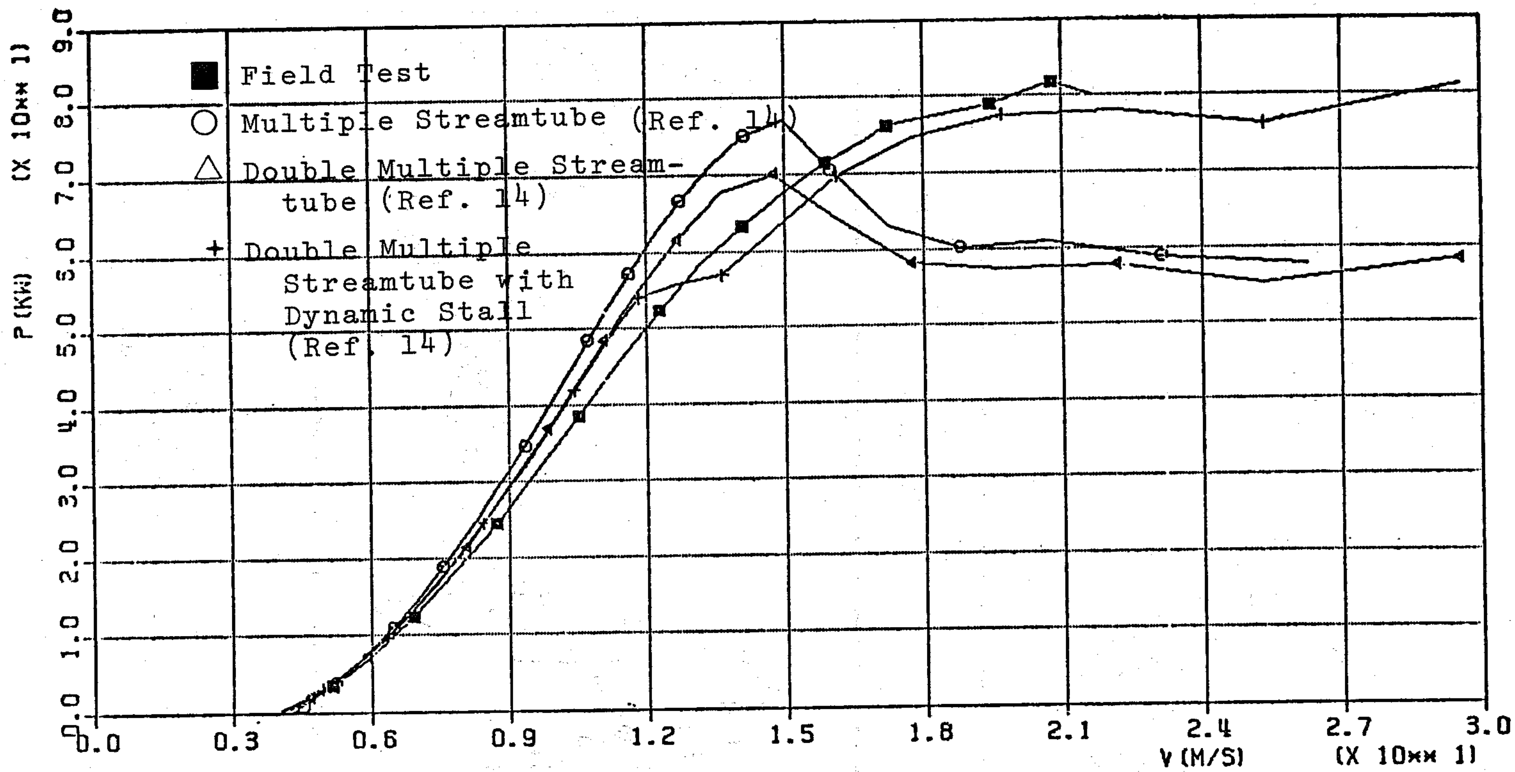

Figure 3. Power vs Windspeed, SNL 17-m-Diameter Research Turbine, 2 Blades, NACA 0015 Section, 61 cm Chord, ω = 50.6 rpm

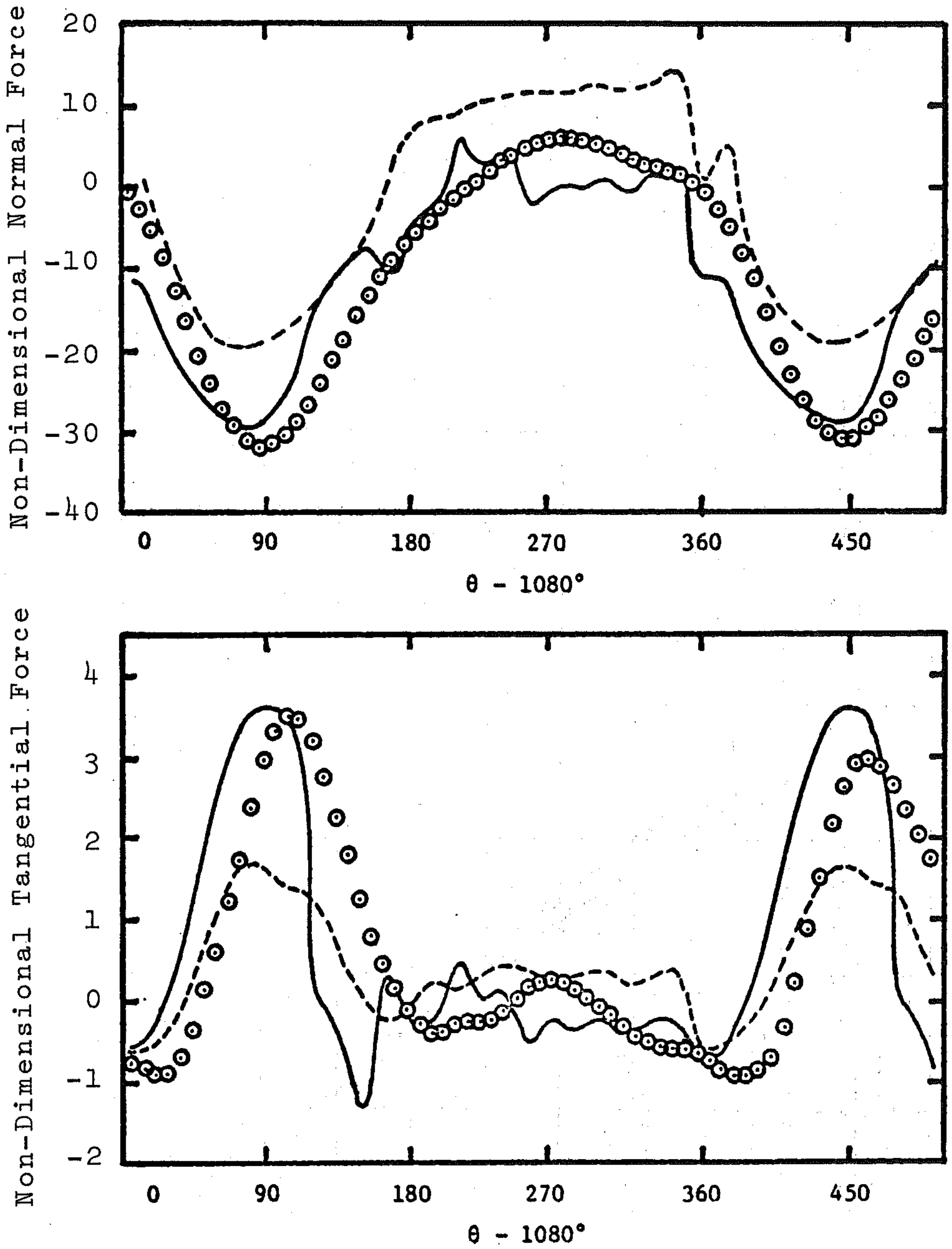

Figure 4. Blade Force Data for a Two-Dimensional Rotor, Ref. 9, (Re = 40,000, N_B = 2, U_∞ = 5.0, ⊙ Tow Tank Data, --- Quasi-steady model, —— Dynamic Model)